# SAR product improvements and enhancements – SARprises –

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## LONG-TERM GOALS

The long-term goal of this project is to utilize the recently established ordering, receiving, and processing capabilities for TerraSAR-X along-track interferometric synthetic aperture radar (along-track InSAR, ATI) data at the University of Miami's Center for Southeastern Tropical Advanced Remote Sensing (CSTARS) for the development of advanced ATI data products, such as surface current fields in narrow rivers, and innovative higher-order data products characterizing, for example, the bathymetry in coastal areas, properties of oceanic internal waves, and the ocean surface wave spectrum, as derived from amplitude signatures, interferometric phase signatures, and polarimetric signatures.

## OBJECTIVES

Within the project period of 36 months (which started in spring 2011), we intended to

- acquire and analyze a comprehensive set of ATI images of rivers, coastal areas, and open-ocean features such as internal waves and tropical storms;
- explore possibilities of obtaining surface current estimates for challenging test sites, such as very narrow rivers (width < 100 m), where most of the backscattered power from a fast-moving water surface may be mapped into pixels on land;
- test techniques for two-dimensional vector current field retrievals from combined TerraSAR-X / TanDEM-X along-track InSAR data or combined single-instrument along-track InSAR data from ascending and descending overpasses of a test site;
- develop tools for the generation of higher-level data products from along-track InSAR-derived surface current fields, such as bathymetric maps of coastal waters and volume flow / mean runoff estimates for rivers of uncertain depth; and
- evaluate the potential of innovative InSAR- and polarimetry-based techniques for fully two-dimensional surface wave retrievals.

These activities will make significant contributions to an improved understanding and an optimal exploitation of the potential of existing and future spaceborne SAR systems for U.S. Navy operations and for a variety of research and engineering applications.

# Report Documentation Page

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## APPROACH

The project consists of six main Work Packages, which are defined as follows.

Work Package 1: CSTARS Upgrades. When the proposal was written, we were planning to implement receiving and processing capabilities for TanDEM-X and COSMO-4 at CSTARS (in addition to existing capabilities for other satellites) and to evaluate the ATI capabilities of COSMO-4 and RADARSAT-2.

Work Package 2: Data Acquisition and Raw Data Processing. This Work Package comprises the collection and processing of a variety of innovative data sets through CSTARS, including new ATI images of several rivers of different widths, of coastal areas with a strong bathymetry-modulated tidal flow, test areas with internal waves and eddies; dual-beam ATI data from TerraSAR-X and TanDEM-X together for vector current retrievals; and combined along-track / cross-track InSAR and polarimetric data of rivers and ocean scenes for a variety of tests. Some data products were already in the TerraSAR-X / TanDEM-X archives of DLR, acquired during the TerraSAR-X Dual Receive Antenne (DRA) mode campaign and the TanDEM-X commissioning phase in 2010.

Work Package 3: Advanced Current Retrieval Techniques. In this work package we will improve our current retrieval capabilities by testing current retrievals over new kinds of features, such as oceanic internal waves, and by developing techniques for narrow rivers and for two-dimensional vector current retrievals. Due to the azimuthal displacement of moving targets in SAR images, most of the signal contributions from narrow water surfaces may be mapped into pixels on land. They must be separated from the contributions of stationary targets and moved back to the correct location in the image to permit meaningful current estimates. We will try an approach that combines advanced interferometric processing of the two original complex SAR images with physics-based statistical modeling of the contributions from water and land and our existing current retrieval procedure for the correction of SAR imaging artifacts and wave contributions over open waters. Two-dimensional vector current retrievals may be obtained by combining data from ascending and descending overpasses, but a more promising development is be based on the idea of simultaneous ATI data acquisitions by TerraSAR-X and TanDEM-X with slightly different look directions. To acquire such data, one of the satellites must be rotated by some angle for a limited time. A demonstration of the dual-beam ATI technique with an airborne system was given Toporkov et al. [1]. Other ideas to be attacked within this Work Package are the combined use of TerraSAR-X and TanDEM-X to cover a larger effective swath or to improve the data quality within the normal swath; multi-baseline along-track interferometry; and a comparison of current fields retrieved from ATI data with results of the Doppler centroid method based on conventional single-channel SAR data (see [2] for an example).

Work Package 4: Advanced Wave Retrieval Techniques. Wave retrieval algorithms for conventional, interferometric, and polarimetric SAR data will be implemented and applied to images acquired in Work Package 1. Results will be compared with each other, with buoy data, and with wave spectra from numerical wave model (WAM) runs. Techniques for combining results of different wave retrieval methods (e.g. based on intensities and phases of interferometric data or on intensities and polarimetric coherences of polarimetric data) will be tested, and the feasibility of phase-preserving wave field retrievals and the detection of freak waves will be evaluated. Combining TerraSAR-X and TanDEM-X data with a short time lag, a retrieval of frequency-wavenumber spectra may be possible. Conclusions regarding optimal wave retrieval strategies and desirable instrument and algorithm improvements for further improved wave retrieval capabilities will be drawn.

Work Package 5: Higher-Level Data Products. The retrieval of bathymetric maps from ATI-derived current fields, requiring only a small number of known depths for deriving a characteristic current-depth relationship for each test area, has been demonstrated in [3]. This existing algorithm will be developed a little further in such a way that it can be applied to new test sites without case-specific optimization and that phases and intensities of ATI images can be analyzed together. Furthermore, visible wave refraction patterns will be included in the analysis. Here we need to account for the dependence of wave signatures in SAR images on the imaging geometry and for effects of SAR imaging artifacts such as velocity bunching. In addition to wave refraction due to changes in the water depth and the corresponding wave velocity according to the shallow-water dispersion relation, some contribution to the modulation of wavelengths and directions of propagation may result from wave-current interaction. We think this contribution can be identified and taken into account in the data interpretation if wave trains propagating in different directions are considered. Furthermore, wave patterns in SAR images acquired at different tidal phases will be subject to different tidal current fields, but a constant bathymetry. At the end of the data processing chain, consistent bathymetric maps should be obtained from all images. In addition to the bathymetry work, an algorithm for river volume flow estimates will be implemented, based on methods discussed in [4] and [5], and techniques for separating tidal contributions from the mean river runoff will be tested on the basis of available long time series of ATI images of rivers. Furthermore, the use of along-track and cross-track InSAR data from TerraSAR-X and TanDEM-X for combined surface curren and water level measurements and corresponding improved volume flow estimates will be tested.

Work Package 6: Dissemination. Results of the project will be disseminated through a project website, presentations at international conferences, and publications in peer-reviewed journals. To ensure an efficient collaboration and data exchange with existing ONR program teams and other potential partners and users, we will contact these colleagues in an early stage of the project, inform them about our objectives, plans, and needs, and establish sustainable communication links.

## WORK COMPLETED

Work Package 1: CSTARS Upgrades. The implementation of new receiving capabilities at CSTARS was almost completed before this project started. Software upgrades for a complete processing of TerraSAR-X and TanDEM-X ATI products at CSTARS were completed in early 2012. In 2013 we completed the development of post-processing tools that correct the standard output of the TerraSAR-X ATI processor for effects of azimuth ambiguities and slow variations in the absolute phase calibration. The final version of COSMO-4 does not have ATI capabilities, thus there is nothing to be tested with COSMO satellites within this project. Furthermore, we have not been able to obtain RADARSAT-2 ATI data within the framework of this project because the Canadians do not make such data available to regular customers.

Work Package 2: Data Acquisition and Raw Data Processing. We have acquired a number of new ATI images from TerraSAR-X and TanDEM-X in 2012 and 2013. Regular Aperture Switching mode images were acquired over the New River inlet and the Columbia River inlet during the experimental phases of the RIVET DRI. This way we have access to a lot of in-situ data and numerical model results for algorithm testing and refinement. A few test images were acquired over potential new test sites of interest, such as the Mekong river delta and Palau. In February and March 2012, a special orbit configuration of TerraSAR-X and TanDEM-X permitted inter-satellite interferometry with near-optimal baselines for current measurements for the first time. We acquired two images at Orkney (Scotland) and obtained very good results. A peer-reviewed journal article on the Orkney results is in press [F]. Other existing combined TerraSAR-X / TanDEM-X datasets include two series of images acquired over the open ocean with slowly changing along-track baselines. These data can be used to determine the dependence of the autocorrelation function of the backscattered signal on the ATI time lag and help to optimize parameters of future ATI systems. A manuscript for a journal article is in preparation. In addition to the newly acquired data, we have obtained a number of interesting datasets from the TerraSAR-X DRA mode campaign in 2010. This includes two very interesting ATI images of internal waves at Dongsha (South China Sea); see Work Package 3. We also have found clear phase signatures of surface wave motions in some images, which will be analyzed when the two above-mentioned manuscripts have been finished. Furthermore, polarimetric images and TerraSAR-X / TanDEM-X image pairs from the TanDEM-X commissioning phase with particularly long time lags will be analyzed to test non-interferometric wave and wind retrieval techniques. We will continue to acquire TerraSAR-X and combined TerraSAR-X / TanDEM-X ATI data in 2013 and 2014. In particular, a dedicated ocean applications campaign with TanDEM-X is planned for October 2014.

Work Package 3: Advanced Current Retrieval Techniques. One important achievement in this task is the successful retrieval of currents over an internal wave at Dongsha from a TerraSAR-X DRA mode image. To our knowledge, this has not been done with satellite data before. Some results are shown in the figures at the end of this report, and a manuscript for a peer-reviewed article will be finalized and submitted in fall 2013. Furthermore, we have developed advanced filtering techniques to remove wave signatures from high-quality phase images obtained with a long along-track baseline (see Work Package 2) and to exploit the wave information for improved corrections. The data obtained at the New River and Columbia River inlets indicate a need to apply different wave motion corrections for the rivers and the open ocean. In these cases, the waves cannot be resolved by the (short-baseline) ATI phase data, but they are visible in the SAR intensity images. Graduate student Conor Smith has started to analyze the wave signatures and associated Doppler and phase variations and to compare them with in-situ data from the experiments and model results. This work will lead to significant improvements in the accuracy and applicability of our wave motion correction algorithms for ATI data. Finally, we will soon begin to test a new current retrieval technique based on spatial shifts in wave patterns in image pairs from the TanDEM-X commissioning phase, with a time lag on the order of 3 seconds.

Work Package 4: Advanced Wave Retrieval Techniques. We do have polarimatric images of waves from the TerraSAR-X DRA mode campaign and very high resolution phase images with pronounced wave signatures from combined TerraSAR-X / TanDEM-X acquisitions. A detailed analysis of these data will begin in early 2014.

Work Package 5: Higher-Level Data Products. We have started to analyze wave patterns in a TerraSAR-X spotlight SAR image to test our ideas about bathymetry retrievals from wave refraction patterns. The results obtained so far are promising. We will try to apply the same technique to ATI data and to combine it with the analysis of spatially varying current fields over bathymetry. This is one of the research topics of graduate student Conor Smith, who started to work in this project in fall 2012.

Work Package 6: Dissemination. We have presented results of this project at an ESA meeting on current measurements in Brest, France, at SeaSAR 2012 in Bergen, Norway [B], at IGARSS 2012 in Munich, Germany, an Ocean Surface Currents meeting at ESA-ESTEC, Netherlands, a TerraSAR-X / TanDEM-X Science Team Meeting at DLR, Germany, and at IGARSS 2013 in Melbourne, Australia. A peer-reviewed paper on current fields at Orkney, Scotland, was accepted for publication in IEEE-TGARS and is currently in press (available on IEEE Xplore as Early Access article) [F]. The manuscripts of two more papers on the internal waves at Dongsha and on the decorrelation of the backscattered signal will be finished and submitted within the coming months, and another one on wave signatures will be written in 2014. Very likely, another manuscript on advanced corrections of ATI data for wave motions will arise from Conor Smith's analysis of New River and Columbia River inlet images. Within the last 12 months, we also published an encyclopedia article on ATI [C], an overview article about the ATI technique and its applications in a scientific magazine [E], and a conference article focusing on close formation flights of satellites for SAR interferometry [A]. The PI's former graduate student in Germany, Steffen Grünler, published a paper on the potential of using spaceborne ATI systems to estimate mean river discharges [D].

## RESULTS

Our combined TerraSAR-X / TanDEM-X results confirm that very-high quality ATI results can be obtained at effective baselines of 25-40 m. We could show that the effective resolution obtained under such conditions can be on the order of 30 m. This is sufficient to resolve wave motions, and we will analyze some observed wave signatures soon. Our series of TerraSAR-X / TanDEM-X images obtained with slowly changing along-track baselines enable us to measure the autocorrelation function of the backscattered signal. Early results indicate that the decorrelation times are a little longer than theoretically predicted ones. Furthermore, the results obtained for the internal wave images indicate that it is feasible to obtain direct measurements of the current variations over an oceanic internal wave from TerraSAR-X ATI data. This permits much more robust estimates of internal wave amplitudes and, thus, pycnocline depths etc. than methods based on radar intensity signatures, since ATI signatures are much less difficult to model and less sensitive to uncertainties in wind estimates (discussed for intensity signatures in [6]). All of this has been done within this project for the first time. Our results will make a significant contribution to a better exploitation of spaceborne ATI capabilities in the future and enable us and other users (in particular the U.S. Navy) to do current and wave measurements from space at a spatial resolution and accuracy that has not been possible before. Furthermore, the achievements of this project will strengthen the reputation of CSTARS as one of the world's leading facilities for the receiving, processing, and higher-level analysis of spaceborne SAR imagery.

## IMPACT/APPLICATIONS

Our new algorithms will permit current and wave retrievals under conditions where they have not been possible before (e.g. current retrievals in narrow rivers, wave retrievals in regions with dominant azimuth-traveling waves) and / or with significantly improved accuracy. The algorithms for higher-order products will facilitate the use of SAR data for a variety of applications and lead to a better utilization of existing spaceborne SAR capabilities for routine applications. The demonstration of high-resolution current measurements with longer baselines may help to pave the way towards dedicated spaceborne ATI systems for ocean and river applications that could be launched within the next 10 years.

## RELATED PROJECTS

All ONR-funded research projects dealing with remote sensing of rivers, tidal flats, and current features and wave spectra in the open ocean, as well as related U.S. Navy op-erations, can benefit from this project. The project has particularly strong connections to the ongoing "Tidal Flats Dynamics" DRI, in which CSTARS and the PI of this project are directly involved, and to the River Inlet (RIVET) projects.

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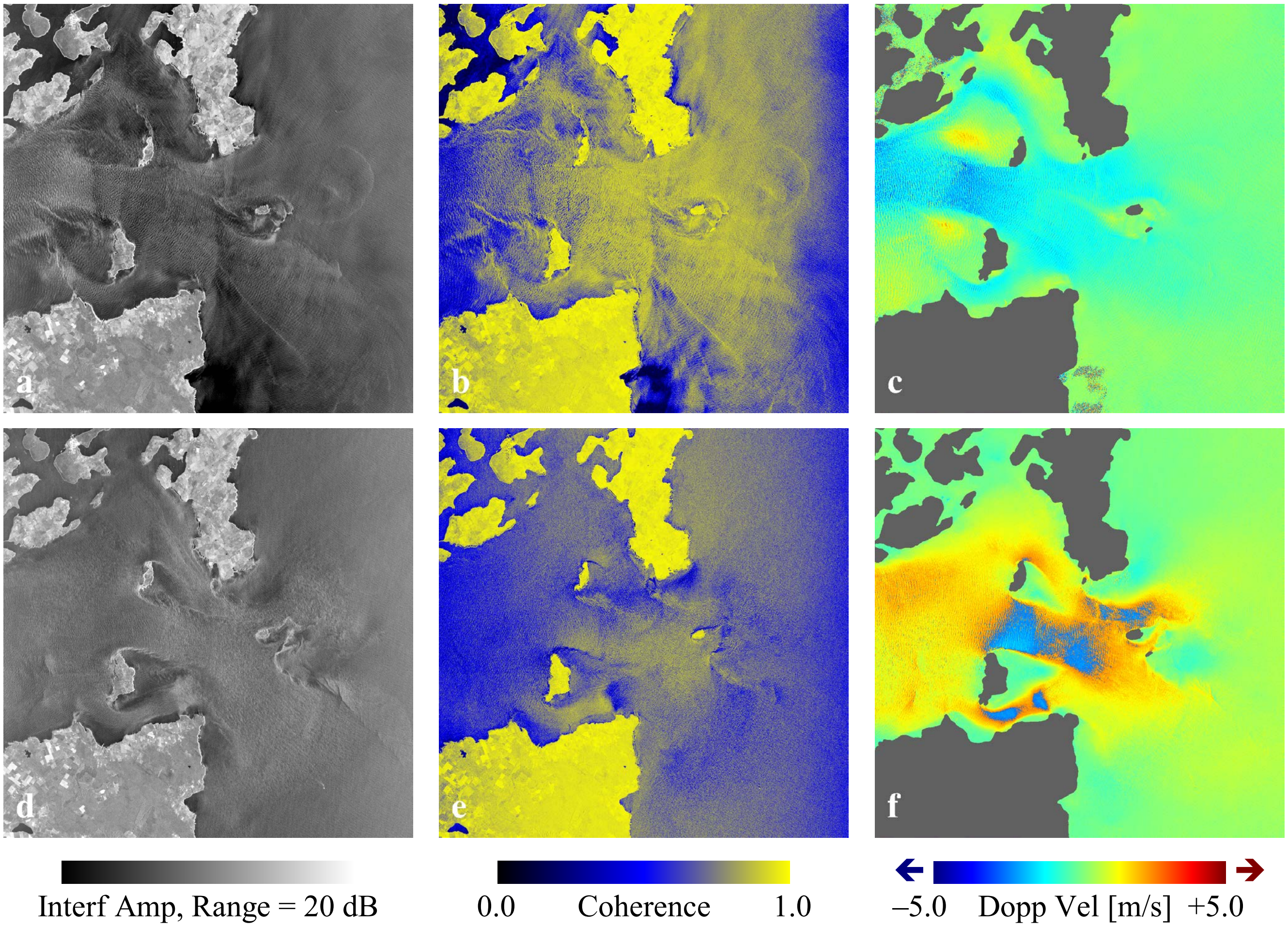


***Fig. 1. TanDEM-X data acquired over Pentland Firth at Orkney, Scotland, on February 26 (top) and March 19, 2012 (bottom), both 06:41 UTC, averaged over 25 m × 25 m grid cells: (a,d) interferogram amplitude, (b,e) coherence, (c,f) phase converted into horizontal Doppler velocity. Shown area size ≈ 30 km × 30 km; radar look direction = from right to left; positive velocity direction = from left to right. While the coherences are not particularly high at effective baselines of 25 m (February 26) and 40 m (March 19), the quality of the phase images is much better than the quality of short-baseline ATI images obtained in the divided-antenna modes of TerraSAR-X. Without further averaging, we see very clear signatures of strong tidal currents between the islands. Artifacts in the center of (f) illustrate the effect of phase wrapping at long baselines, which can be easily corrected in this case. From [F].***

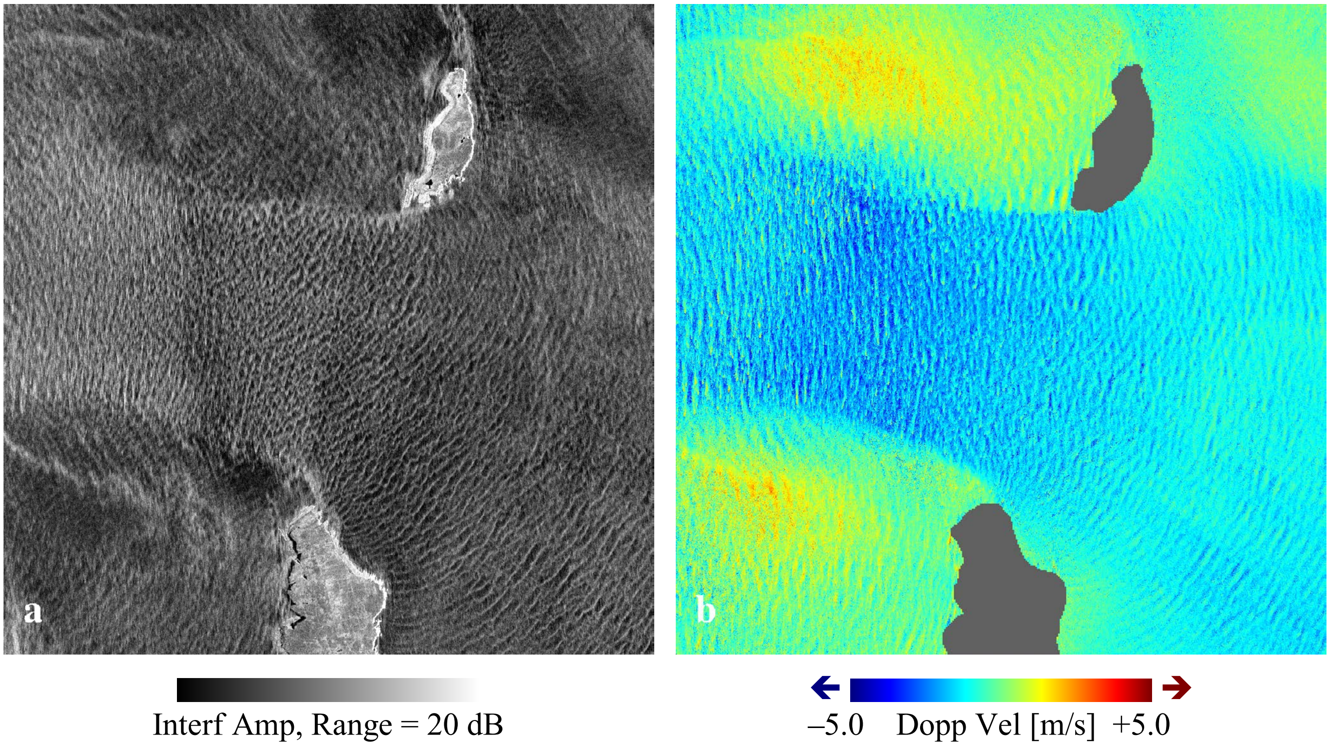


***Fig. 2. Magnified subsections of Figs. 1a and c (February 26, 2012), showing wave signatures in the interferogram (a) amplitude and (b) phase converted into horizontal Doppler velocity. Here the full-resolution data were averaged over smaller grid cells of 8.40 m × 8.46 m (5 × 4 full-resolution samples per grid cell); shown area size ≈ 10 km × 10 km. We are planning to analyze these data for a future publication. From [F].***

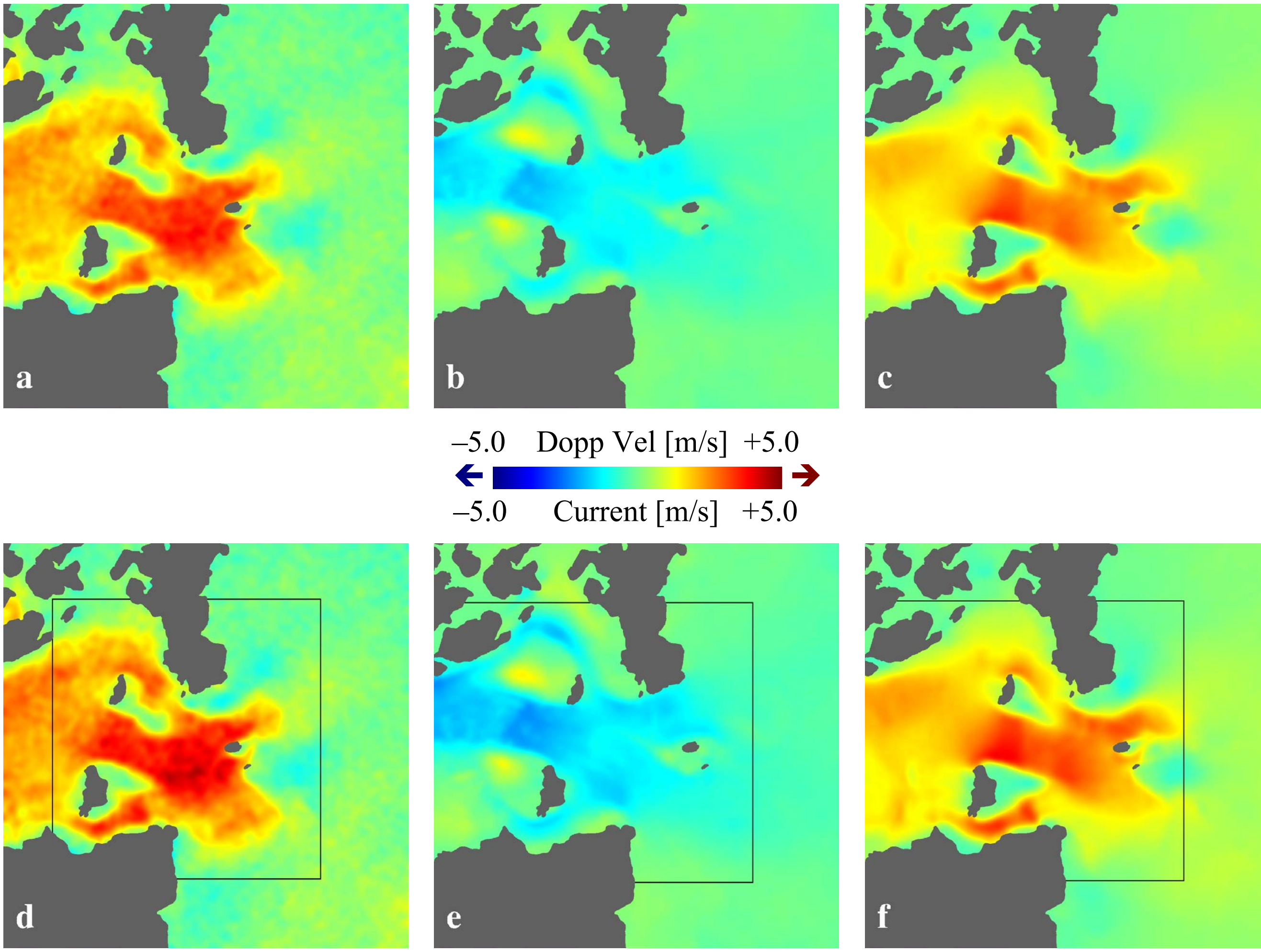


***Fig. 3. Smoothed Doppler velocity (top) and corrected line-of-sight current fields (bottom) derived from a TerraSAR-X DRA Mode dataset (not shown before in this document; first column) and the datasets of Figs. 1 (second and third columns). The correction of the ATI-derived velocities for contributions of wave motions does not have a strong effect in these cases. Note that the two TanDEM-X results look much smoother than the TerraSAR-X DRA Mode result. From [F].***

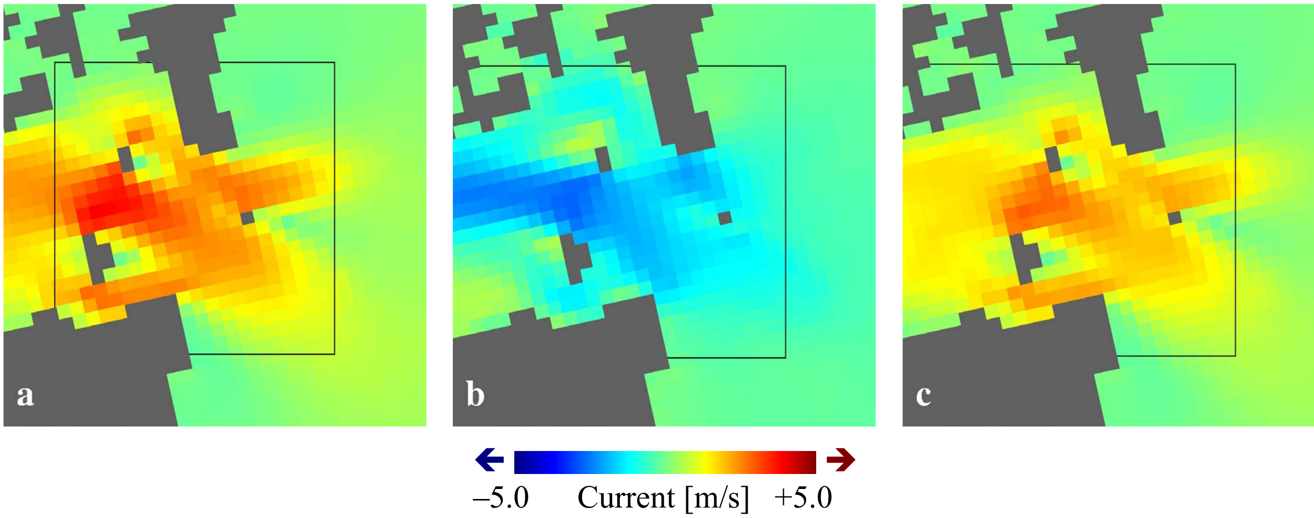


***Fig. 4 Line-of-sight current fields in the test area from the numerical tide computation system POLPRED for (a) April 26, 2010, (b) February 26, 2012, and (c) March 19, 2012, all 06:41 UTC. The agreement with the TerraSAR-X and TanDEM-X ATI-derived currents (Fig. 3) is good. From [F].***